Putting Synergies into Actions: Integration of Nuclear and Renewables in Competitive Electric Markets

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Pathways to Decarbonization: An International Workshop to Explore Synergies Between Nuclear and Renewable Energy Sources
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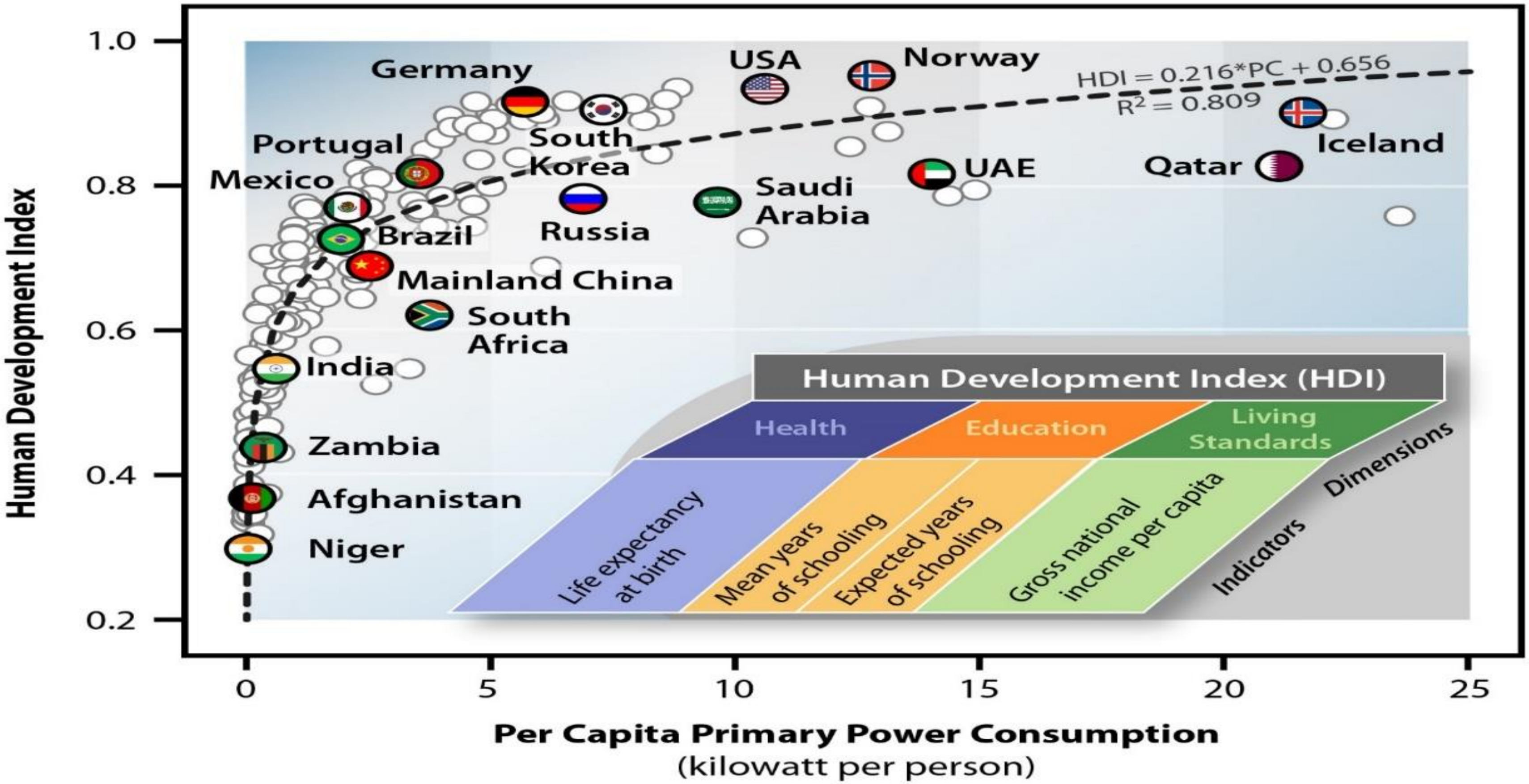
Human Development Index Tied to Energy Consumption



There is a Moral Imperative to Meet Energy Demands for Human Development

Historically Local Variations in Renewable Energy Resources Determined Standards of Living and Military Power

- Biofuels (food and grass) determined standards of living and population densities
- Military power (knights) required grass for horses
- The great powers had greener grass (literally) and more food
  - France
  - England

The Development of Fossil Fuels (Cheap Energy) Raised Standards of Living

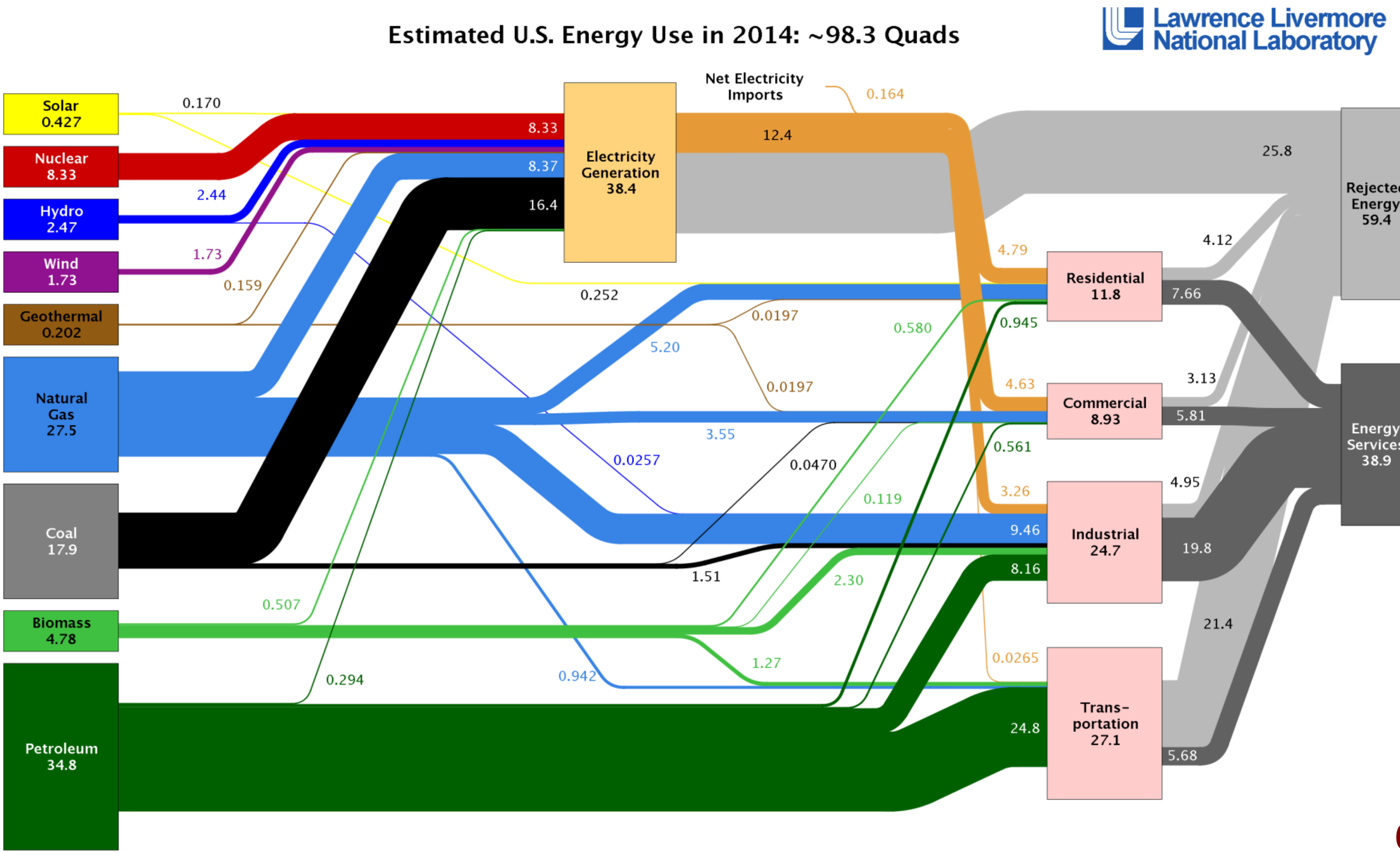
Then
Low-Cost
Fossil-Fuel
Transport
<u>Globally</u>
<u>Equalized</u>
<u>Energy</u>
<u>Costs</u>

Fossil Fuels Enabled Low-Cost Variable Energy—From Electricity to Liquid Fuels

Economics Based on Low-Capital-Cost Systems with Storable Fuels

Natural Gas Combined-Cycle Plant

Fossil Fuels Meet Electricity and Multiple Non-Electricity Energy Demands



Requirements for Replacing the Fossil Fuel Energy System

Reasonably Priced Energy Across the Globe
(Energy Today ~10% Global Economy)

Meet Variable Energy Demand
(Daily through Seasonal Variations)

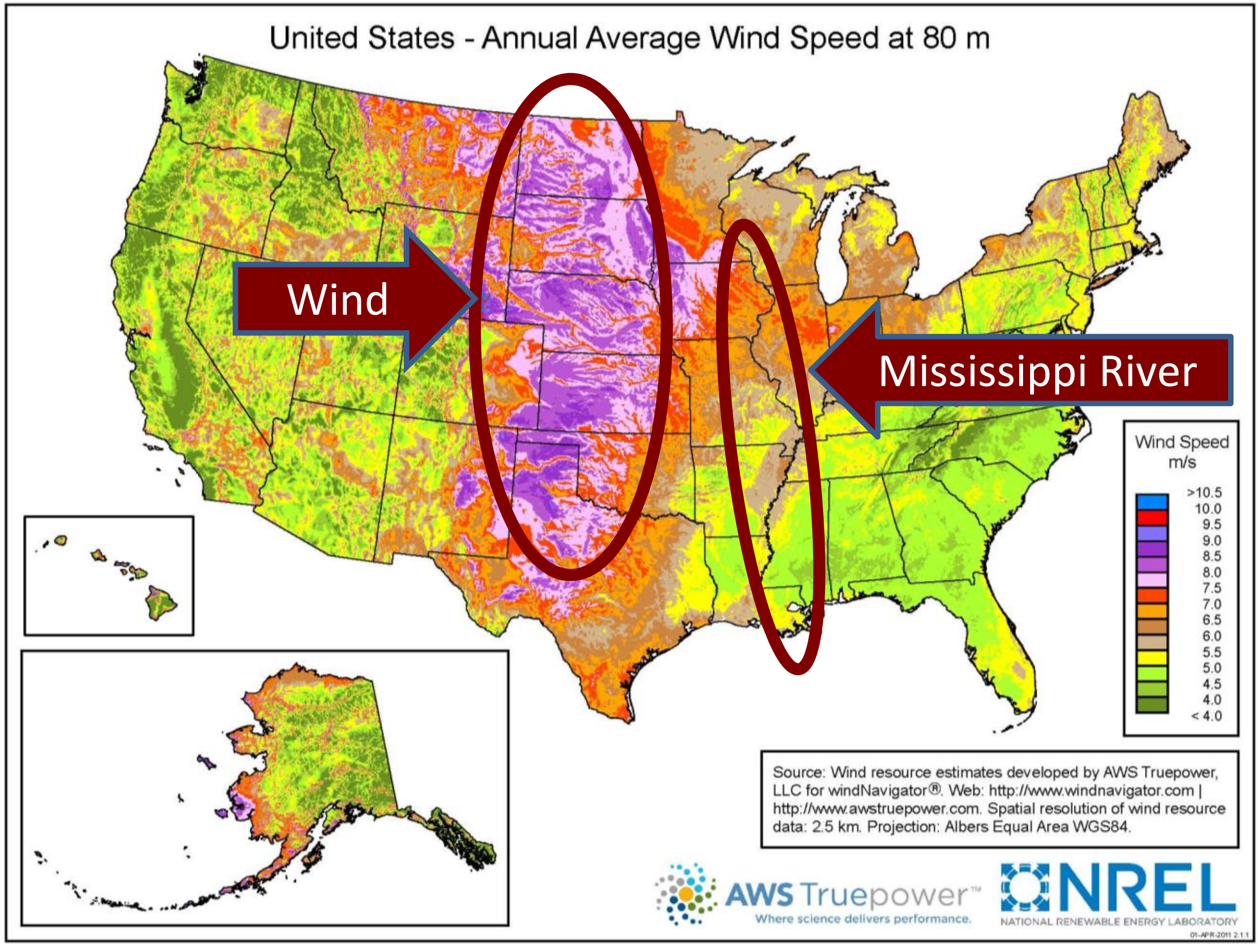
Meet Multiple Energy Needs
(Electricity, fuel, heat)

Characteristics of Low Carbon Technologies

Nuclear Power Costs Can Be Similar Everywhere Because Uranium Transport Costs are Low

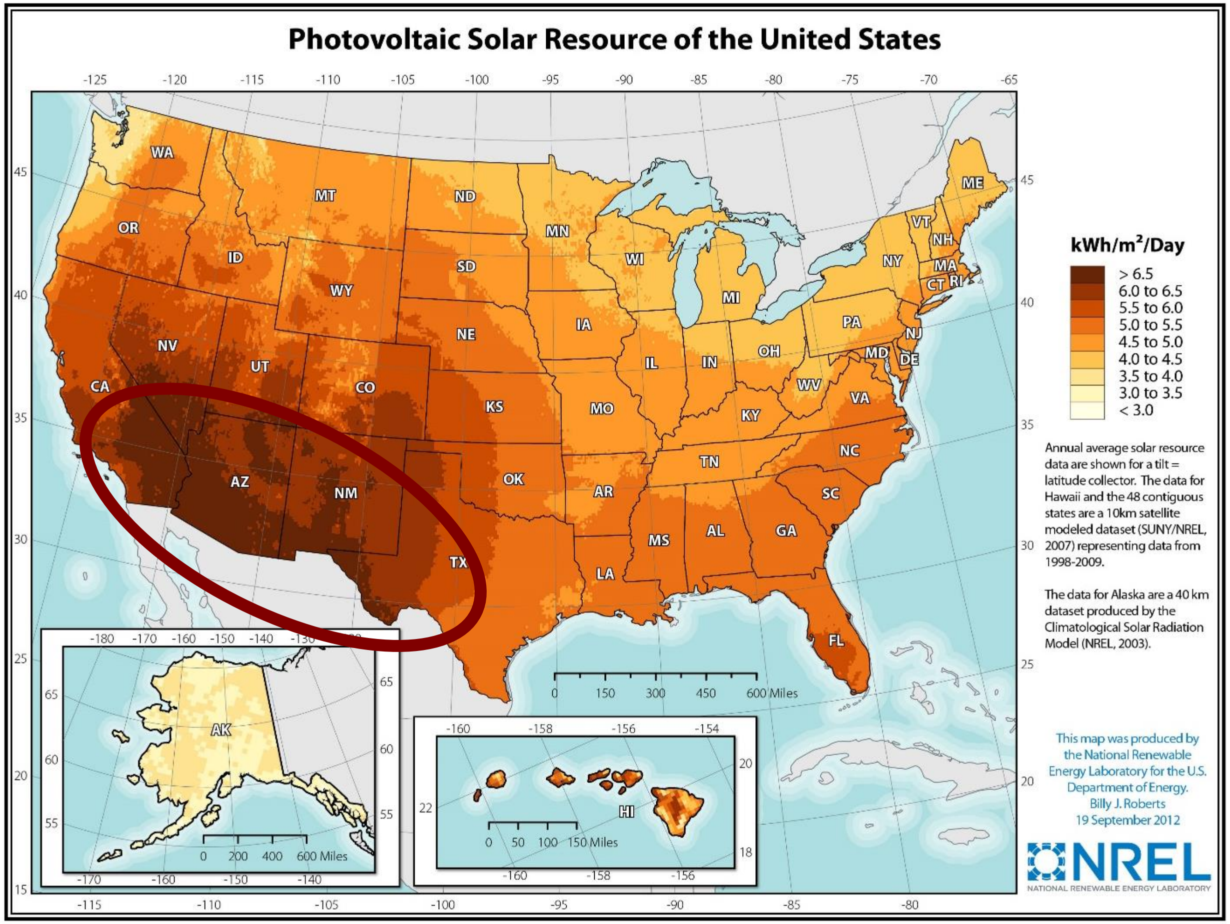
Wind Distribution Is Highly Uneven

Does a Wind Energy Future in the U.S. Move Jobs and Industry to Between the Great Plains (Energy) and the Mississippi River (Water and Transport)?



Solar Distribution Is Highly Uneven

Water and Other Constraints in Southwest



Low-Carbon Electricity Storage Requirements

All Nuclear, Solar or Wind California Future (% Total Electricity)

Electricity Production Method	Hourly Storage Demand	Seasonal Storage Demand
All-Nuclear Grid	0.07	0.04
All-Wind Grid	0.45	0.25
All-Solar Grid	0.50	0.17

Storage Costs Could Determine Economic Energy Sources

Implications of Low-Carbon Nuclear, Solar, Wind World

Future Energy Systems Will Be More Diverse than in a Fossil World

Large Regional Cost Variations of Wind and Solar Imply Large Differences in Relative Amounts of Nuclear, Wind, and Solar with Location

Going from Fossil-Fuel to Low-Carbon Electricity Changes Economic Model

Low-capital-cost Fossil Plants Can Operate Economically at Part Load

Fossil Fuel Electricity
Low Capital Cost
High Operating Cost

Low-Carbon Electricity
High Capital Cost
Low Operating Cost

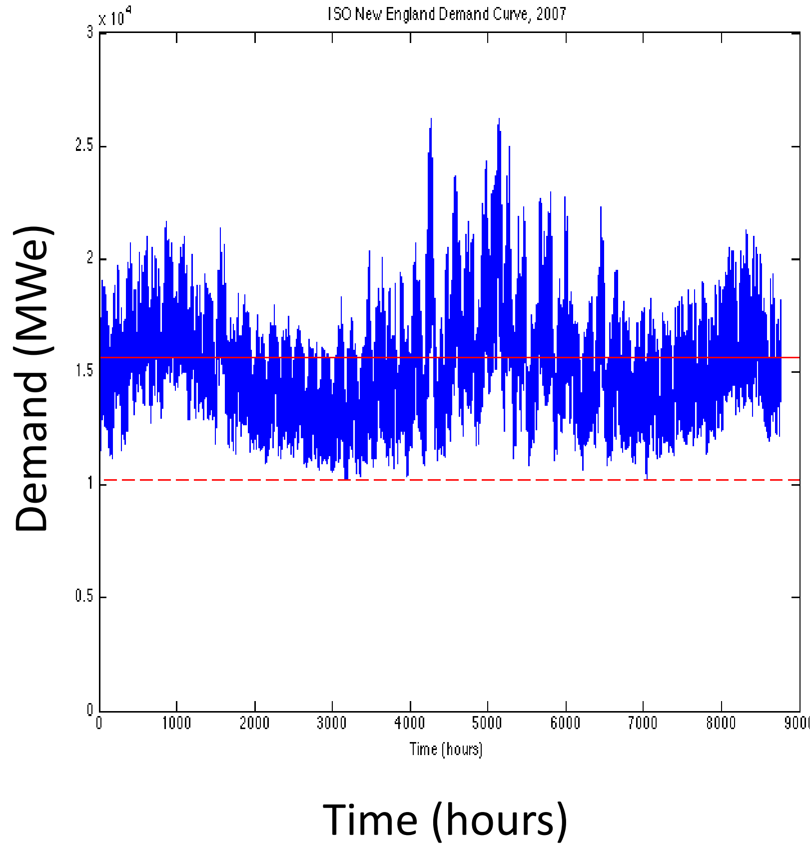
Low-Carbon Electricity is Only Economic If Operate Nuclear, Wind, Solar Capital-Intensive Plants at Full Capacity

2020 U.S. Levelized Electricity Costs ($/MWh)

Plant type	Capacity factor (%	Levelized capital cost	Fixed O&M	Variable O&M (including fuel)	Trans. invest	Total system LCOE
Dispatchable Technologies						
NG Combined Cycle	87	14.4	1.7	57.8	1.2	75.2
NG Turbine	30	40.7	2.8	94.6	3.5	141.5
Advanced Nuclear	90	70.1	11.8	12.2	1.1	95.2
Non-Dispatchable Technologies (High Wind and Solar Zones)						
Wind	36	57.7	12.8	0.0	3.1	73.6
Wind – Offshore	38	168.6	22.5	0.0	5.8	196.9
Solar PV	25	109.8	11.4	0.0	4.1	125.3
Solar Thermal	20	191.6	42.1	0.0	6.0	239.7

New Plant EIA Projections ($/MWh) in 2013 Dollars

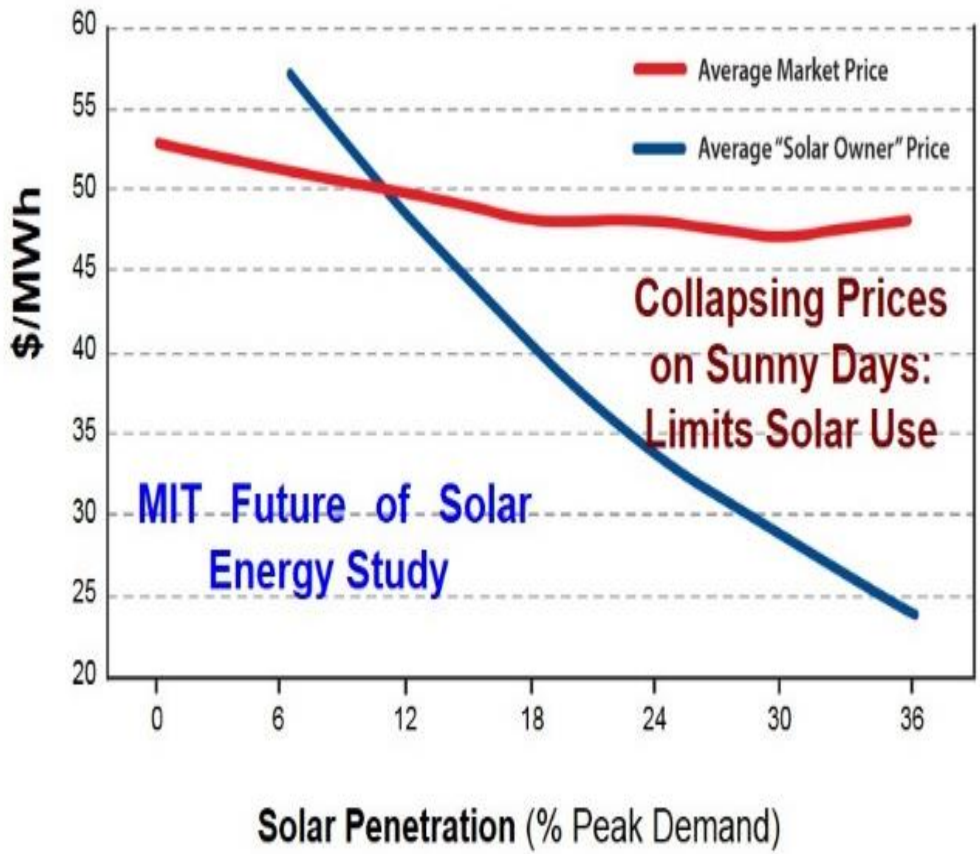
No Combination of Nuclear & Renewables Output Matches Demand



Low-Carbon Electricity Requires New Technologies to Match Electricity Production with Demand

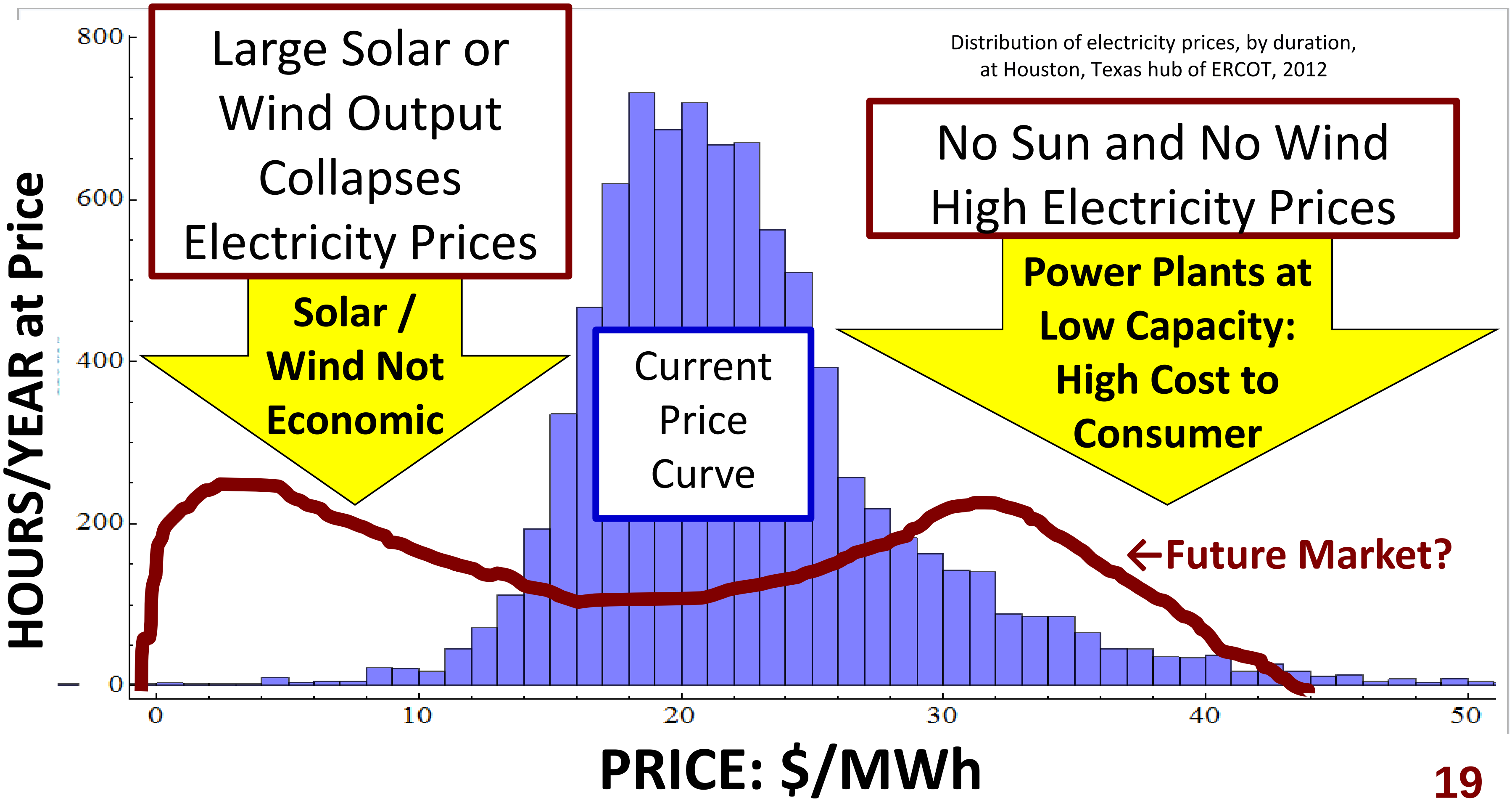
In Competitive Markets, Solar Revenue Collapses as Solar Output Increases

- Price collapse is a characteristic of large-scale use of low-operating-cost high-capital-cost technologies.
- Becomes significant when fraction of total electricity is
  - 10% solar
  - 20% wind
  - 70% nuclear
- Does not happen with fossil-fuel plants



Same Effect If Large-Scale Wind

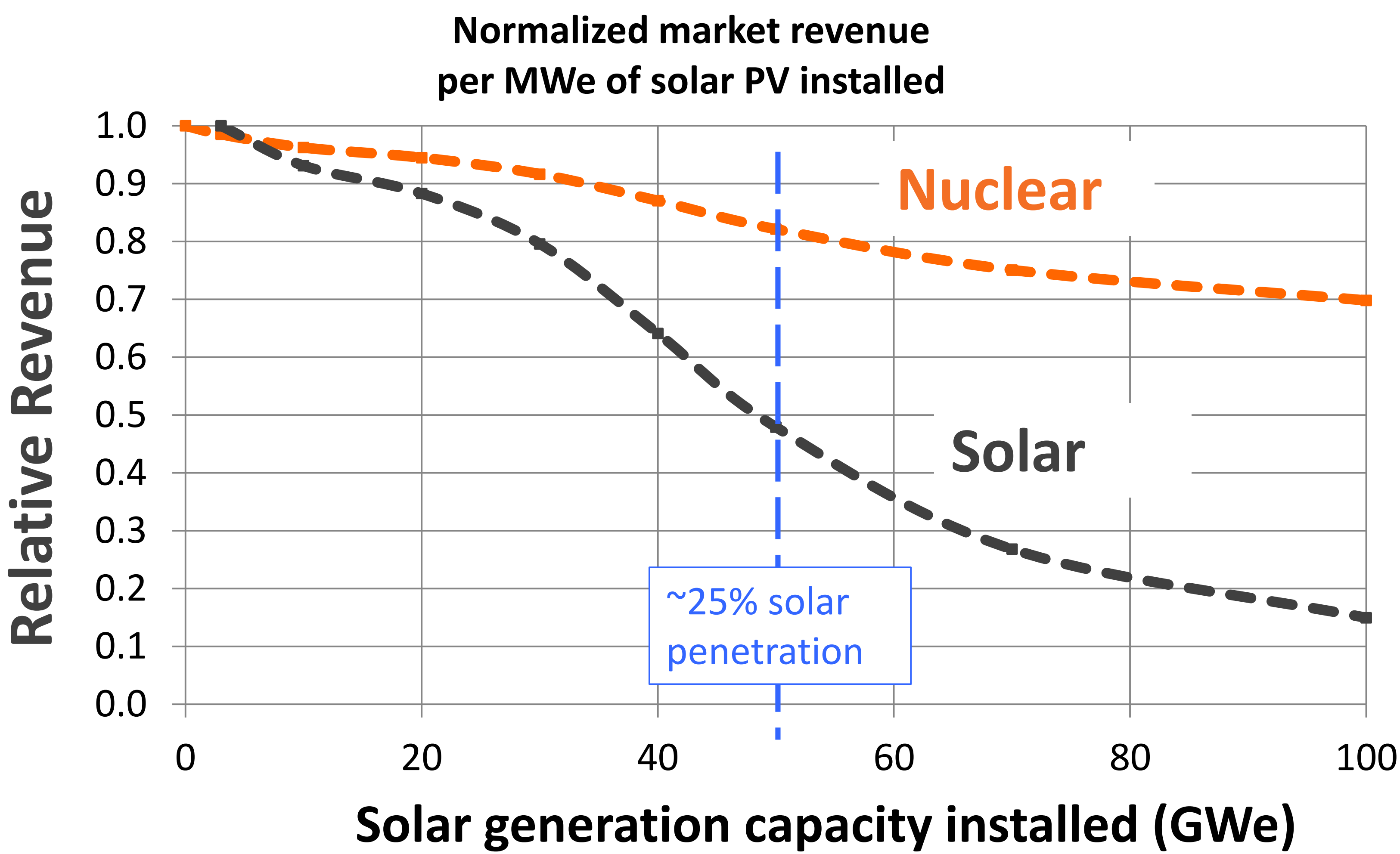
Low-Carbon Nuclear-Renewable Grid Changes Electricity Price Structure



How Do We Use Excess Electricity to Avoid Price Collapse and Create Economically Viable Low-Carbon System?

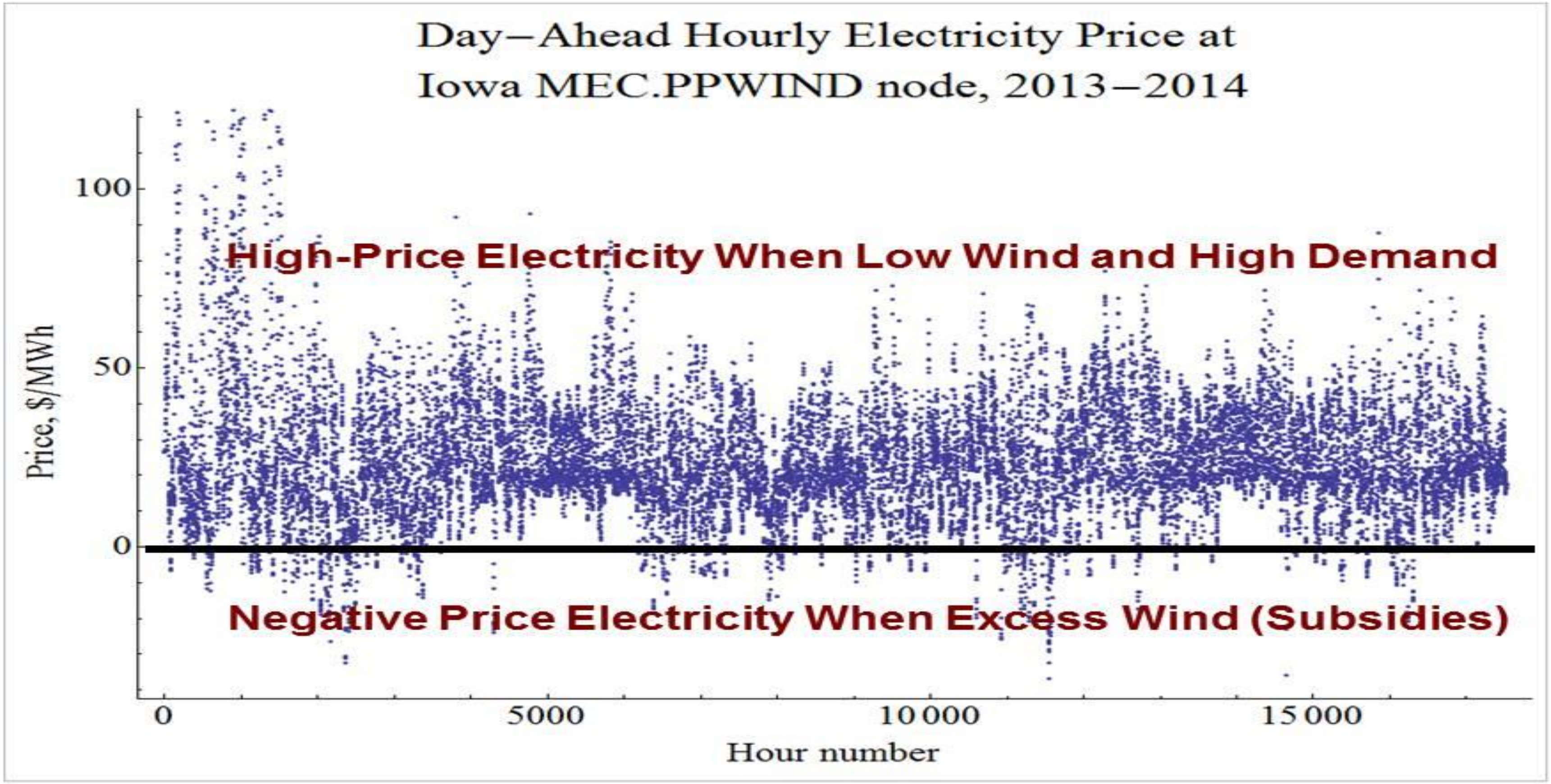
Large-scale Renewables Crash Electricity Prices: Limits Nuclear, Wind and Solar

Simulation of Deregulated Tokyo Grid (Assume half of nuclear Capacity Restarts)



Price Collapse is Real (Wind): Western Iowa

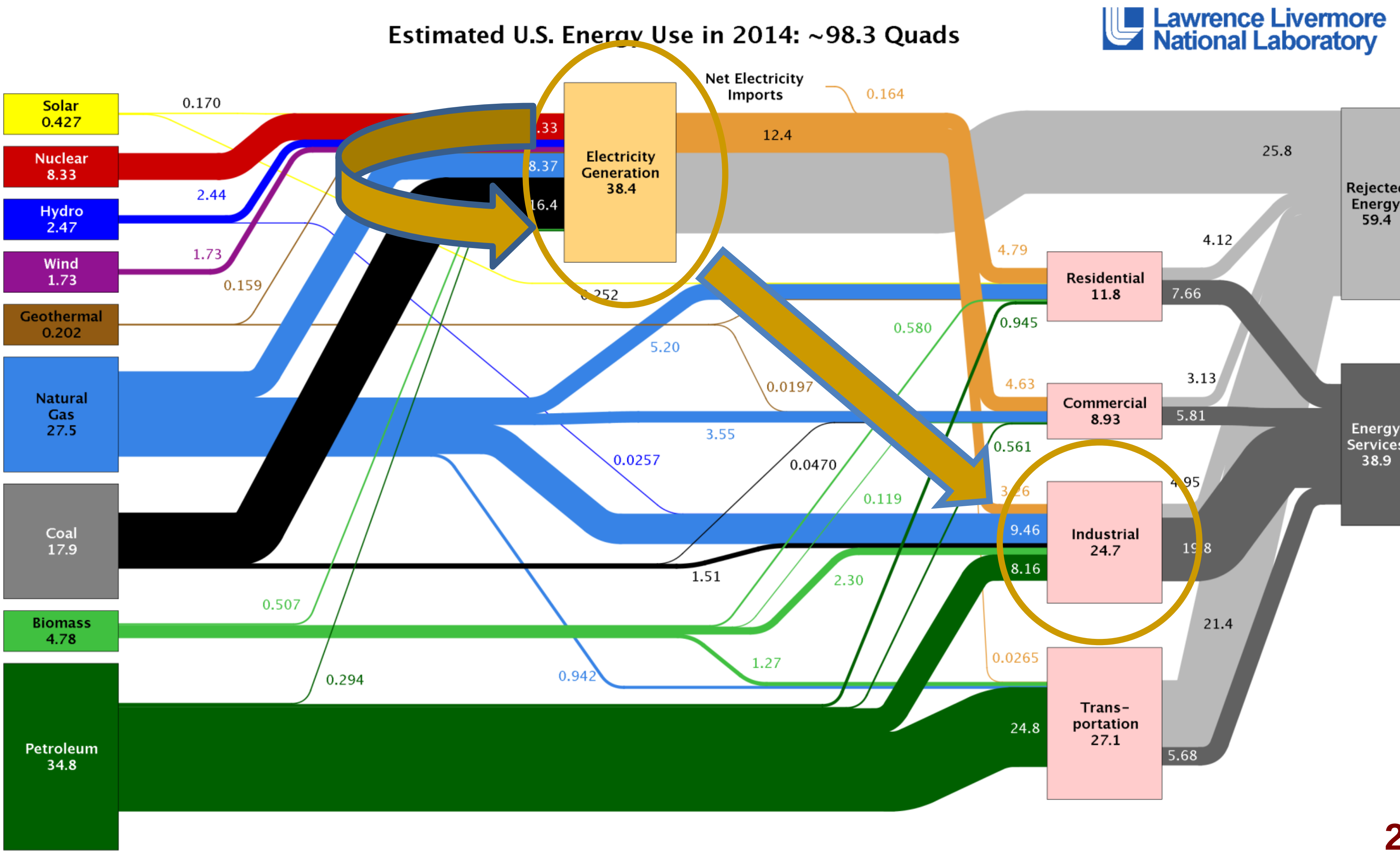
Wholesale Electricity Prices: Two Years



Collapsing Market Limits Wind Deployment

Need Productive Use of Excess Electricity

Two Choices with Large Year-Round Demand:
Industry (Heat) and Peak Electricity (Via Storage)



Pathway to a Low-Carbon Nuclear Renewable Energy System

Strategies to Move Excess <u>Electricity</u> (Work) from the Electric Sector for Full Utilization of Assets

Wind

Nuclear

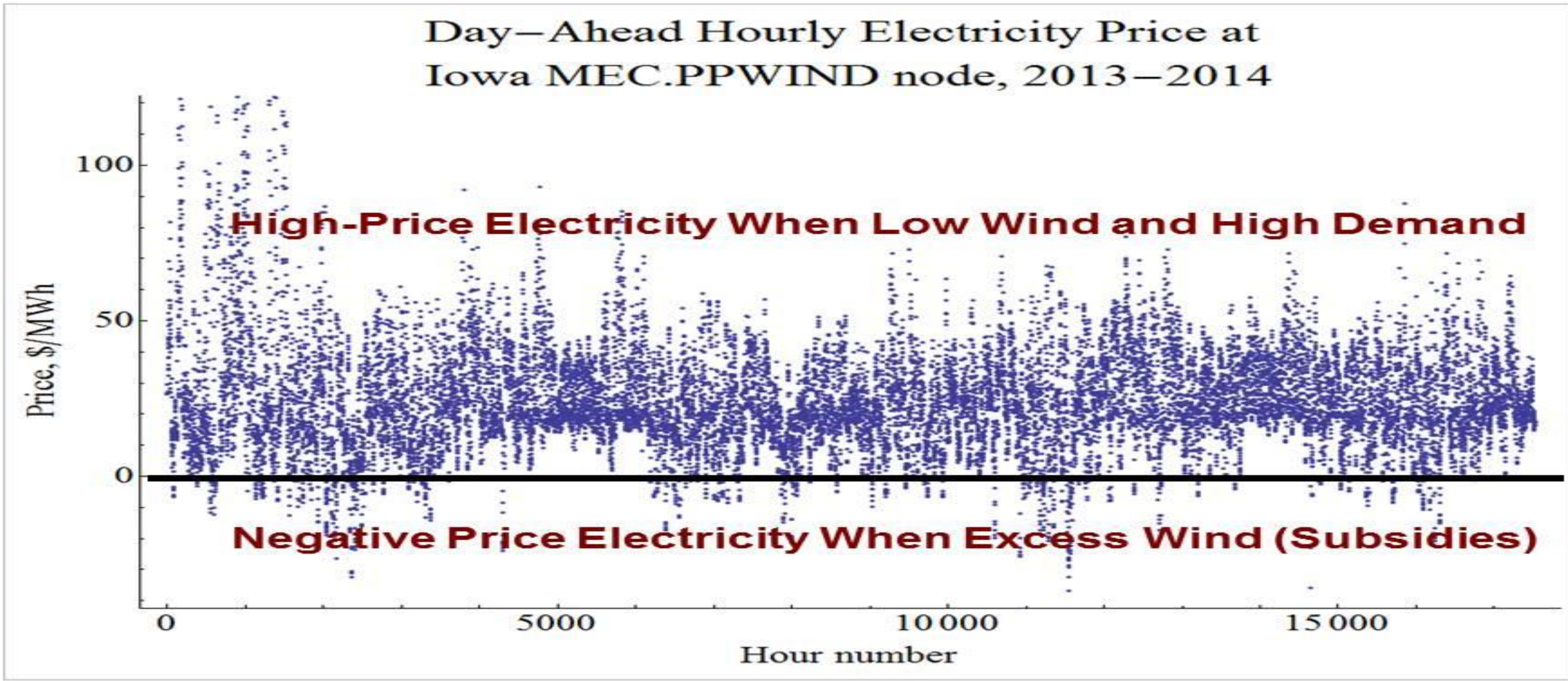
Photovoltaic

- Electricity storage (pumped storage, batteries, etc.)
- Variable production of electricity-intensive storable products in large demand (hydrogen)
- Convert electricity to high-temperature stored heat (Firebrick Resistance-Heated Energy Storage)
    - To industry
    - To peak electricity

Firebrick Resistance-Heated Energy Storage: (FIRES)

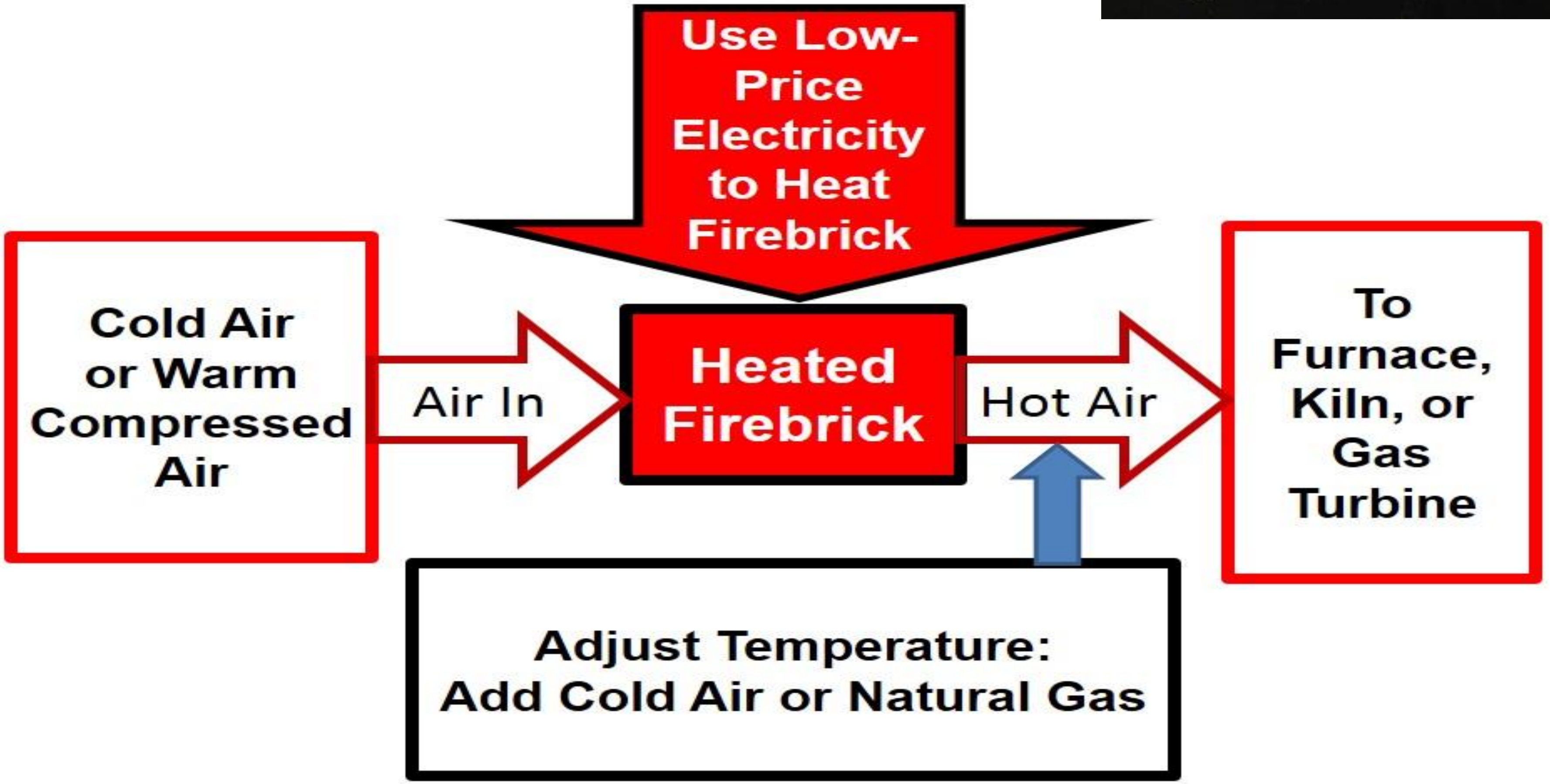
- Buy electricity whenever prices are less than the price of natural gas
- Convert electricity into high-temperature stored heat
- Use stored heat to provide hot air as full or partial substitute for hot air provided by natural gas to:
  - Industrial furnaces and kilns
  - Thermal electricity plants (steam, gas turbine)
- **Creates a minimum price of electricity near the price of fossil fuels**

Half the Time Western Iowa Electricity Prices are Below Local Prices for Natural Gas



FIRES Sets a Minimum Price Near That of Electricity

FIRES Converts Electricity to High-Temperature Stored Heat for Use in Industry and Peak Electricity Production



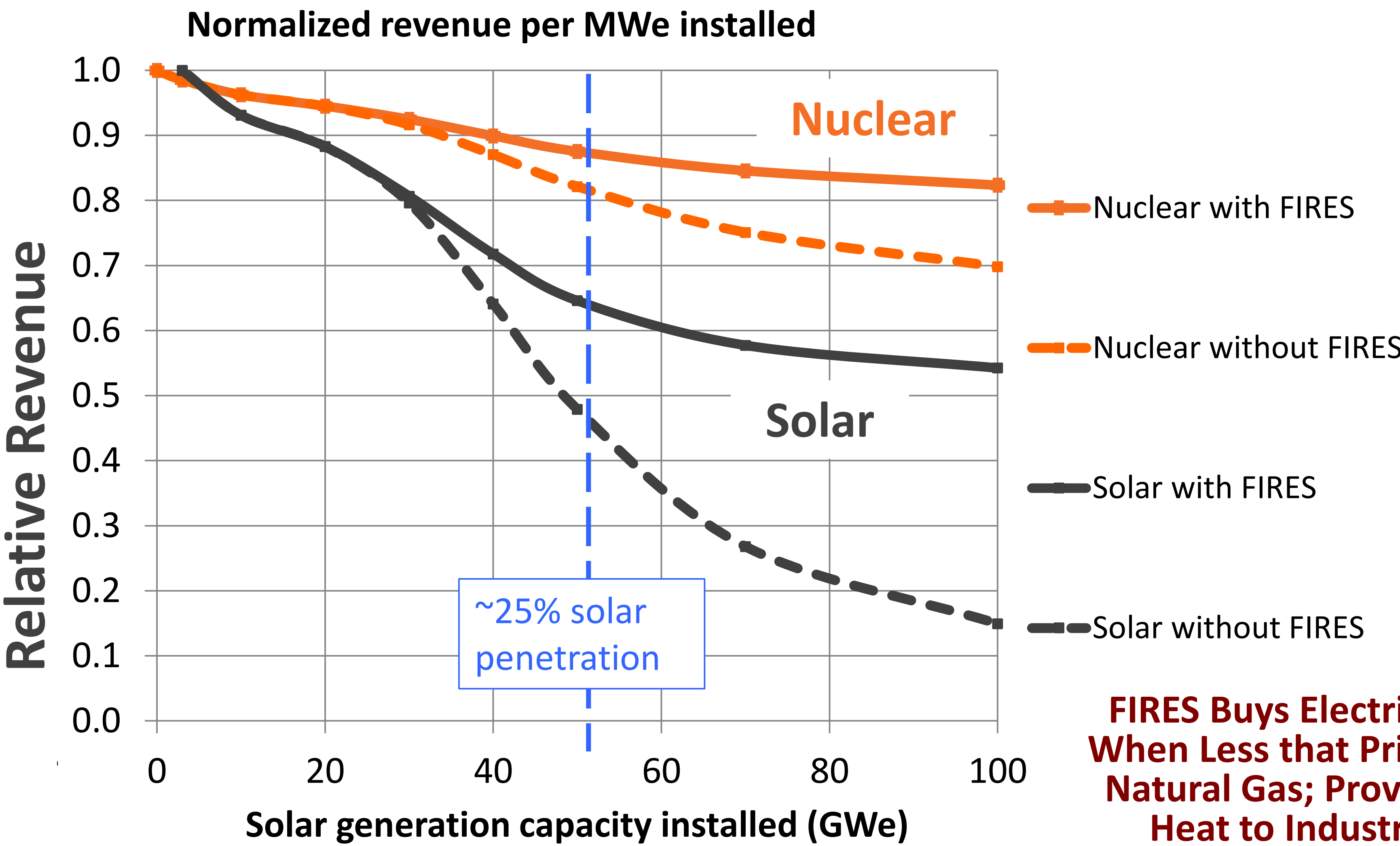
Partly Replace Natural Gas in Industry and Peak Electricity

FIRES Is the Lowest Cost Technology To Consume Low-Price Electricity

Nothing Else Is Even Close

- Industrial FIRES (atmospheric pressure) cost estimate: $5-10/kWh
- Firebrick (clay sent through a kiln): $1-2 kWh
- Electric resistance heating is the lowest cost system that uses electrical energy (Dollars per kW)
  - Voltage across resistance heater to match distribution line voltage —avoid expensive transformers with electrical losses
  - Solid state power supply—avoid expensive AC/DC conversion systems associated with batteries and avoid batteries
- **Factor of 30+ less than batteries using 1920s technologies except for power supply switch**

FIRES Limits Revenue Collapse for Nuclear and Solar in Japan (Tokyo)



FIRES Buys Electricity When Less that Price of Natural Gas; Provides Heat to Industry

FIRES Options for Peak Electricity

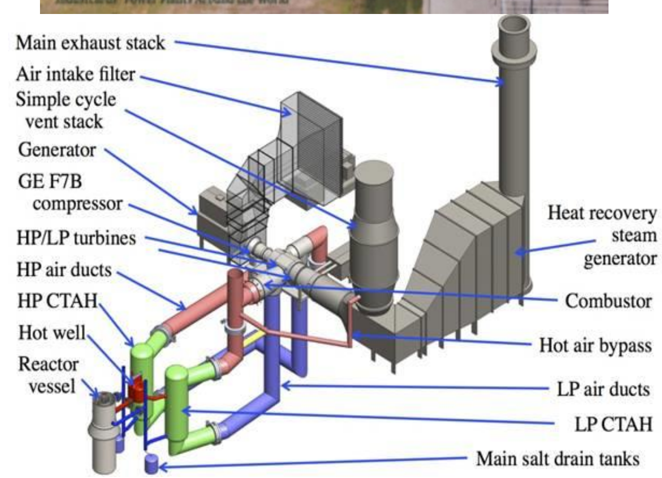
Partial or Full Replacement for Natural Gas/Batteries

Electricity to Heat to Electricity Efficiency

FIRES Replaces Coal as Heat Source for Steam Plant — **42%**

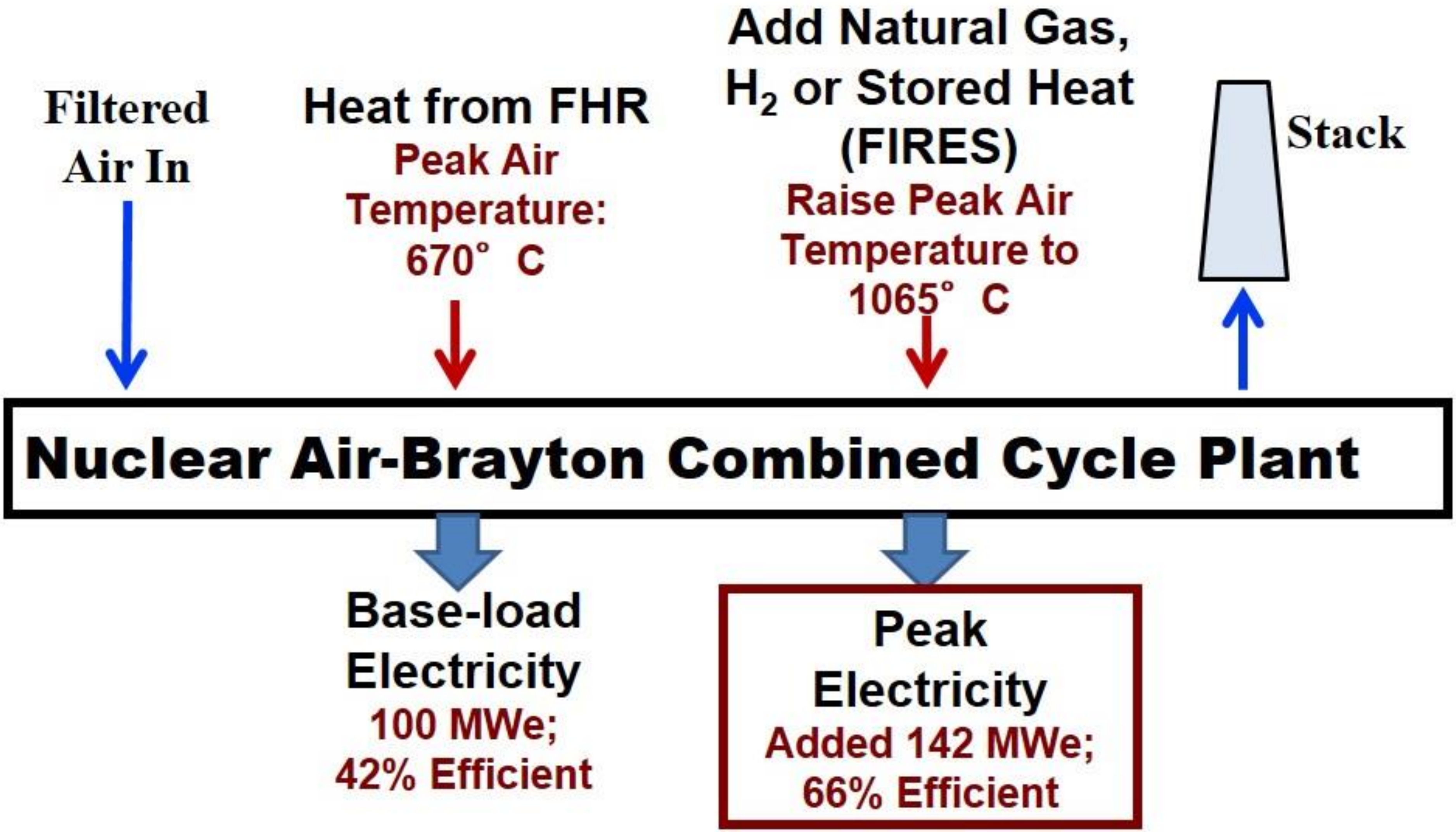
FIRES with Natural Gas Combined Cycle Plant to Reduce NG Use: — **60%**

FIRES with Nuclear Air-Brayton Combined Cycle (NACC): Base-load Nuclear Reactor With Variable Electricity to Grid — **67 to 70 %**



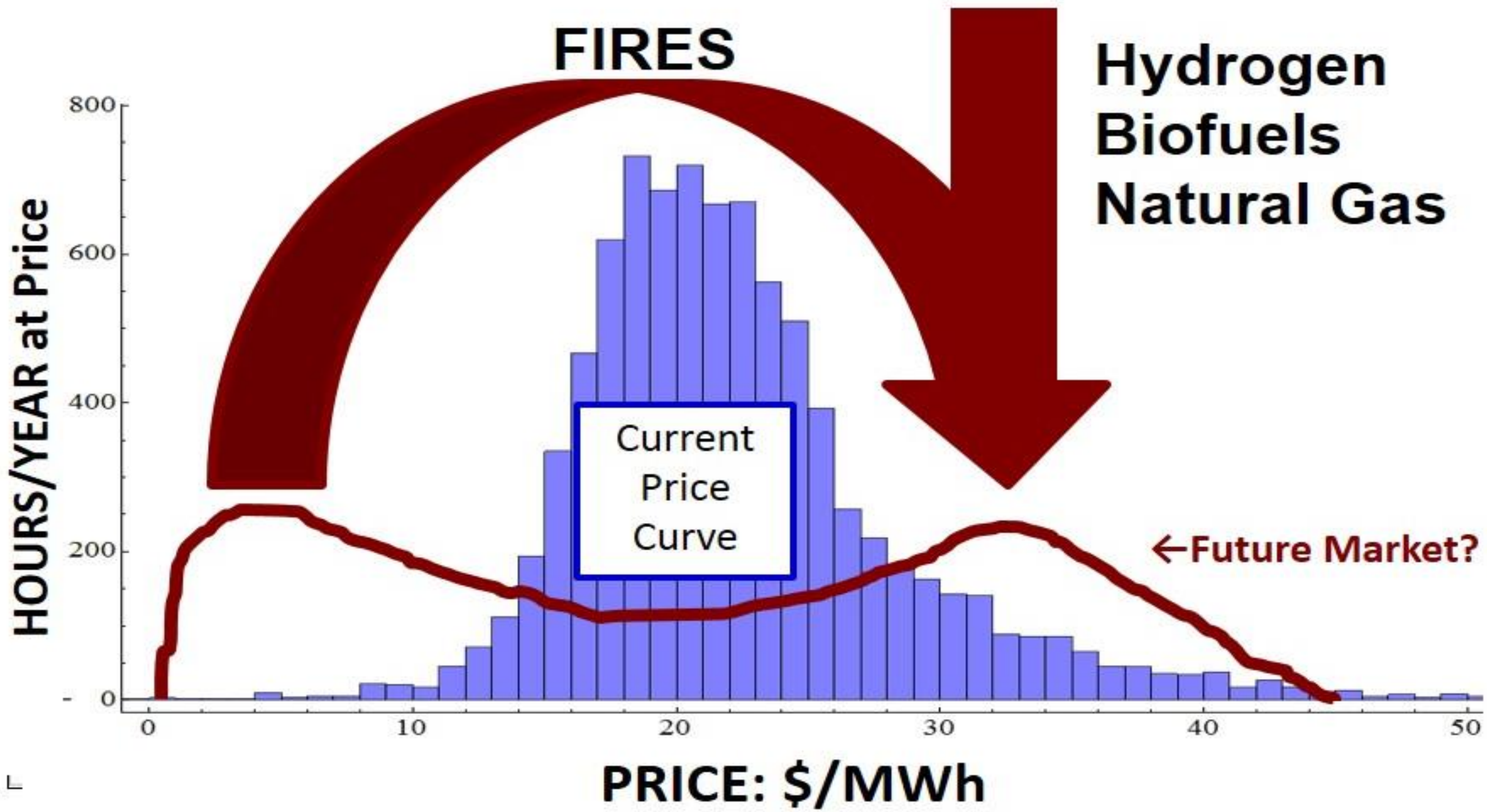
Reactor with NACC and FIRES Has Auxiliary Heat Topping Cycle

More Efficient Than Stand-Alone Natural Gas Plant



Reactor/NACC/FIRES Buys Electricity and Raises Electricity Prices When Low

Reduces Renewable Price Collapse to Sell Electricity When Needed: Nuclear-Renewable Enabling Technology



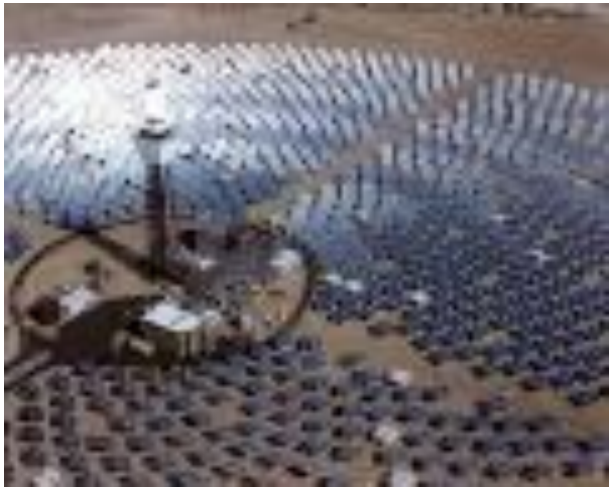
FIRES In All Its Configurations Enables Transition to Zero-Carbon Grid

- Sets minimum price on electricity near fossil fuel price by moving excess electricity as stored heat to industrial sector or for peak power
- If limits on fossil fuels (greenhouse tax, cap and trade, etc.), as fossil fuel prices go up, raise the minimum price for electricity
- More heat to industry and higher minimum prices for electricity favoring solar, wind and nuclear
- **No locational or other such limits**

Strategies to Move Excess Heat from the Electric Sector For Full Utilization of Assets

Nuclear

Concentrated Solar Power



- To Industry
- To Heat Storage for Industry and Peak Electricity

Conclusions-I

- Three energy requirements
  - Affordable
  - Meet variable energy demand
  - Meet all energy needs (electricity, heat, etc.)
- Replacing fossil fuels is tough
  - Wind and solar are local
  - Nuclear, wind and solar outputs do not match demand
- Low-carbon world implies excess electricity generation capability part of the time
  - Can't afford high-capital-cost equipment operating at part load
  - Several options to transfer excess electricity to industry and use to generate peak electricity.

Conclusions-II

- Developing better nuclear, wind and solar systems will not by themselves get us to an affordable low-carbon energy system
- Require low-cost integrating technologies
  - Hybrid energy systems
  - Hydrogen
  - Electricity storage
  - FIRES (heat storage)
- **Large incentives to work together to meet the technical, economic and social challenge**

Biography: Charles Forsberg

Dr. Charles Forsberg is the Director and principle investigator of the High-Temperature Salt-Cooled Reactor Project and University Lead for the Idaho National Laboratory Institute for Nuclear Energy and Science (INEST) Nuclear Hybrid Energy Systems program. He is one of several co-principle investigators for the Concentrated Solar Power on Demand (CSPonD) project. He earlier was the Executive Director of the MIT Nuclear Fuel Cycle Study. Before joining MIT, he was a Corporate Fellow at Oak Ridge National Laboratory. He is a Fellow of the American Nuclear Society, a Fellow of the American Association for the Advancement of Science, and recipient of the 2005 Robert E. Wilson Award from the American Institute of Chemical Engineers for outstanding chemical engineering contributions to nuclear energy, including his work in hydrogen production and nuclear-renewable energy futures. He received the American Nuclear Society special award for innovative nuclear reactor design on salt-cooled reactors and the 2014 Seaborg Award. Dr. Forsberg earned his bachelor's degree in chemical engineering from the University of Minnesota and his doctorate in Nuclear Engineering from MIT. He has been awarded 12 patents and has published over 200 papers.

United States Energy Information Agency: Table 1. Estimated levelized cost of electricity (LCOE) for new generation resources, 2020

		U.S. average levelized costs (2013 $/MWh) for plants entering service in 2020[1]						
Plant type	Capacity factor (%)	Levelized capital cost	Fixed O&M	Variable O&M (including fuel)	Transmission investment	Total system LCOE	Subsidy[2]	Total LCOE including Subsidy
Dispatchable Technologies								
Conventional Coal	85	60.4	4.2	29.4	1.2	95.1		
Advanced Coal	85	76.9	6.9	30.7	1.2	115.7		
Advanced Coal with CCS	85	97.3	9.8	36.1	1.2	144.4		
Natural Gas-fired								
Conventional Combined Cycle	87	14.4	1.7	57.8	1.2	75.2		
Advanced Combined Cycle	87	15.9	2.0	53.6	1.2	72.6		
Advanced CC with CCS	87	30.1	4.2	64.7	1.2	100.2		
Conventional Combustion Turbine	30	40.7	2.8	94.6	3.5	141.5		
Advanced Combustion Turbine	30	27.8	2.7	79.6	3.5	113.5		
Advanced Nuclear	90	70.1	11.8	12.2	1.1	95.2		
Geothermal	92	34.1	12.3	0.0	1.4	47.8	-3.4	44.4
Biomass	83	47.1	14.5	37.6	1.2	100.5		
Non-Dispatchable Technologies								
Wind	36	57.7	12.8	0.0	3.1	73.6		
Wind – Offshore	38	168.6	22.5	0.0	5.8	196.9		
Solar PV[3]	25	109.8	11.4	0.0	4.1	125.3	-11.0	114.3
Solar Thermal	20	191.6	42.1	0.0	6.0	239.7	-19.2	220.6
Hydroelectric[4]	54	70.7	3.9	7.0	2.0	83.5		

[1]Costs for the advanced nuclear technology reflect an online date of 2022.
[2]The subsidy component is based on targeted tax credits such as the production or investment tax credit available for some technologies. It only reflects subsidies available in 2020, which include a permanent 10% investment tax credit for geothermal and solar technologies. EIA models tax credit expiration as follows: new solar thermal and PV plants are eligible to receive a 30% investment tax credit on capital expenditures if placed in service before the end of 2016, and 10% thereafter. New wind, geothermal, biomass, hydroelectric, and landfill gas plants are eligible to receive either: (1) a $23.0/MWh ($11.0/MWh for technologies other than wind, geothermal and closed-loop biomass) inflation-adjusted production tax credit over the plant's first ten years of service or (2) a 30% investment tax credit, if they are under construction before the end of 2013. Up to 6 GW of new nuclear plants are eligible to receive an $18/MWh production tax credit if in service by 2020; nuclear plants shown in this table have an in-service date of 2022.
[3]Costs are expressed in terms of net AC power available to the grid for the installed capacity.
[4]As modeled, hydroelectric is assumed to have seasonal storage so that it can be dispatched within a season, but overall operation is limited by resources available by site and season.
Source: U.S. Energy Information Administration, Annual Energy Outlook 2015, April 2015, DOE/EIA-0383(2015).